Structural Dynamic Assessment of the GN2 Piping System for NASA's New and Powerful Reverberant Acoustic Test Facility

(NASA TM 2012-217610)

ABSTRACT

The National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) has led the design and build of the new world-class vibroacoustic test capabilities at the NASA GRC's Plum Brook Station in Sandusky, Ohio, USA from 2007-2011. SAIC-Benham has completed construction of a new reverberant acoustic test facility to support the future testing needs of NASA's space exploration program and commercial customers.

The large Reverberant Acoustic Test Facility (RATF) is approximately 101,000 ft^3 in volume and was designed to operate at a maximum empty chamber acoustic overall sound pressure level (OASPL) of 163 dB. This combination of size and acoustic power is unprecedented amongst the world's known active reverberant acoustic test facilities.

Initial checkout acoustic testing was performed on March 2011 by SAIC-Benham at test levels up to 161 dB OASPL. During testing, several branches of the gaseous nitrogen (GN2) piping system, which supply the fluid to the noise generating acoustic modulators, failed at their "t-junctions" connecting the 12 inch supply line to their respective 4 inch branch lines. The problem was initially detected when the oxygen sensors in the horn room indicated a lower than expected oxygen level from which was inferred GN2 leaks in the piping system. In subsequent follow up inspections, cracks were identified in the failed "t-junction" connections through non-destructive evaluation testing.

Through structural dynamic modeling of the piping system, the root cause of the "t-junction" connection failures was determined. The structural dynamic assessment identified several possible corrective design improvements to the horn room piping system. The effectiveness of the chosen design repairs were subsequently evaluated in September 2011 during acoustic verification testing to 161 dB OASPL.

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Presentation Outline

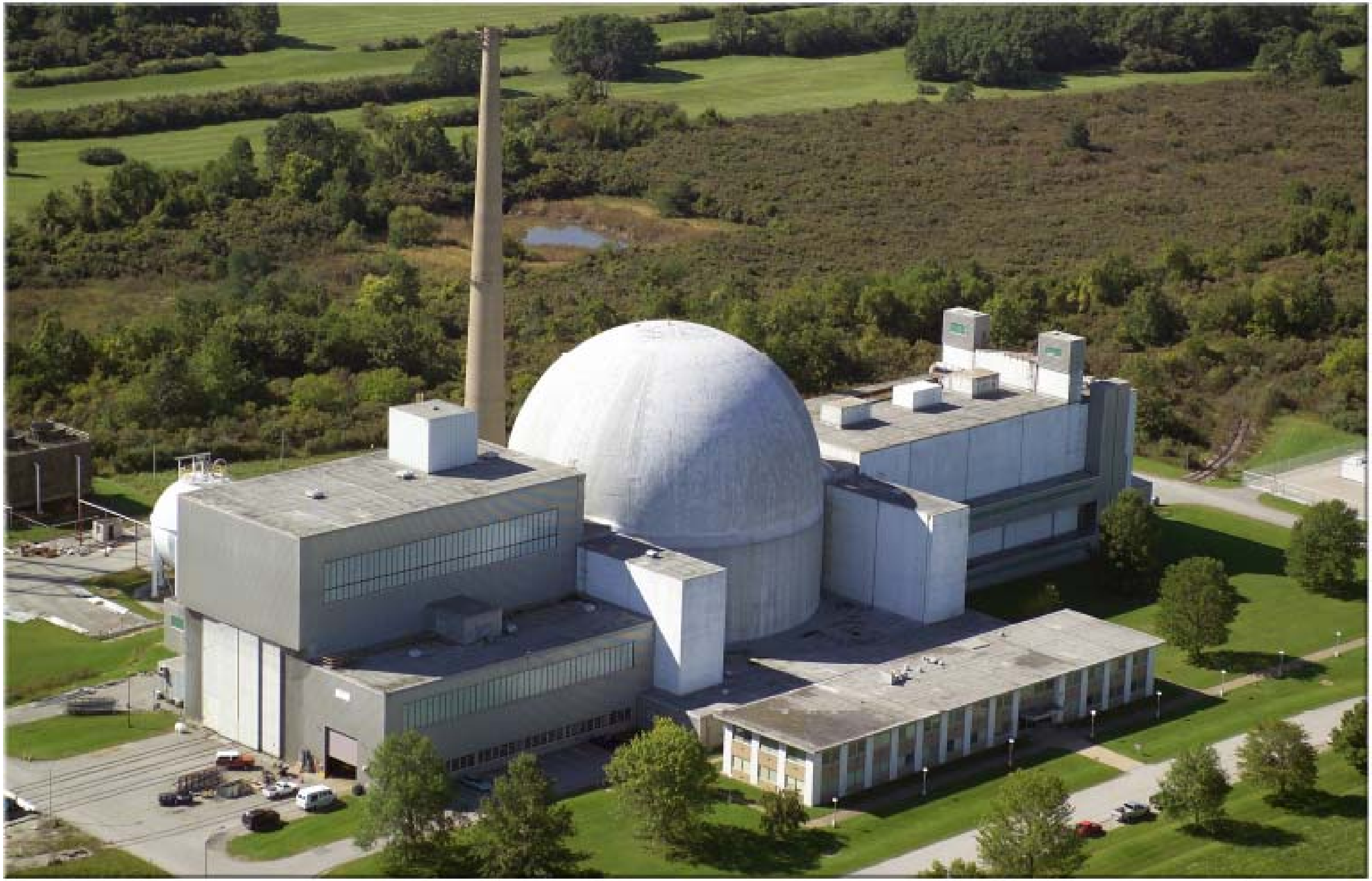
- Introduction
- Horn Room Piping Analysis and Repair
- Acoustic Verification Testing
- Summary

Introduction

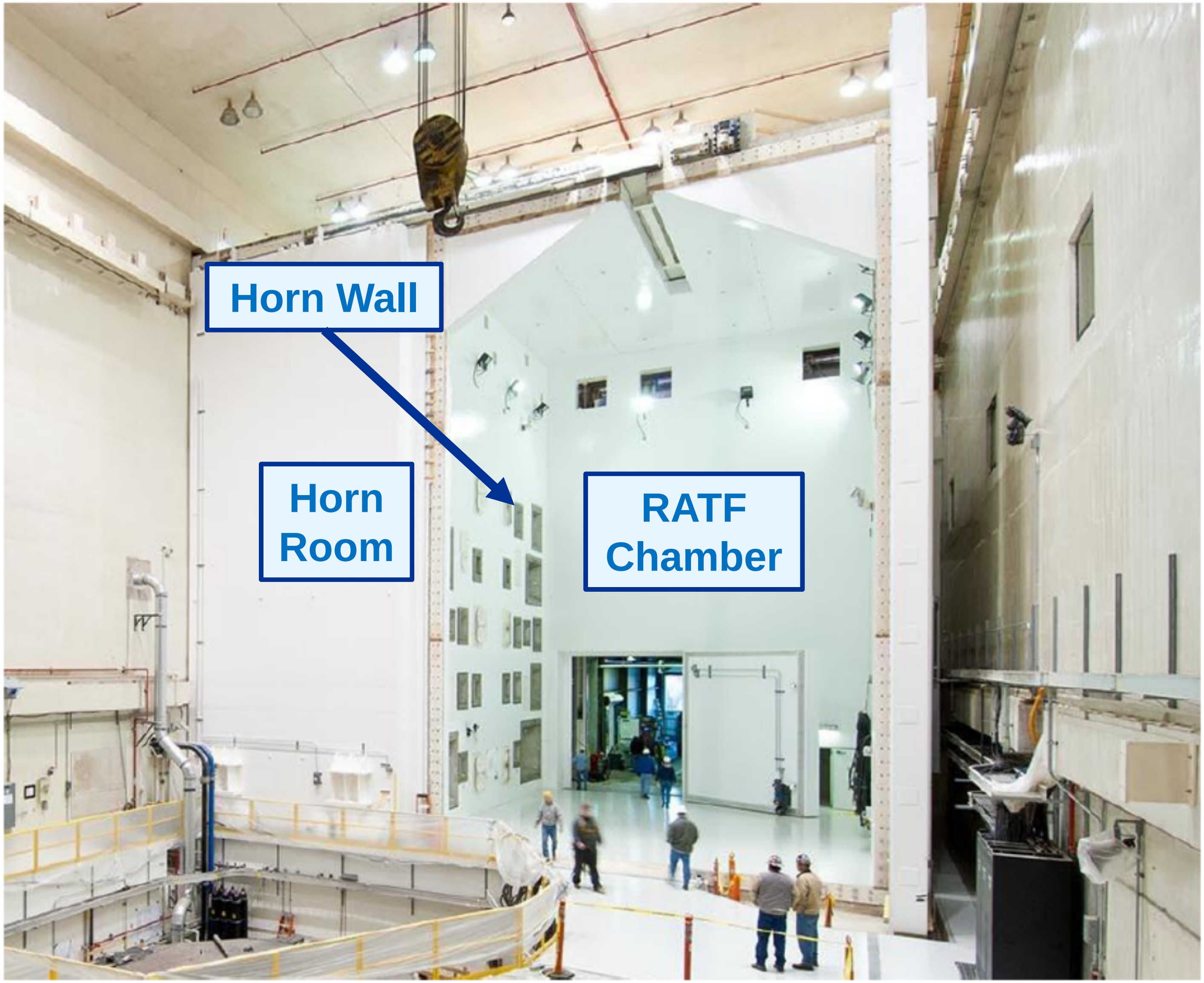
Introduction

- To support NASA's space exploration program, new test facilities were constructed within the NASA Glenn Plum Brook Station's Space Power Facility to provide one-stop environmental testing.
- SAIC-Benham Corporation designed and built the new **Reverberant Acoustic Test Facility (RATF).**
- Construction was completed in February 2011.
- Acoustic verification testing to 161 dB overall sound pressure level (OASPL) was successfully completed in September 2011.

Space Power Facility, NASA Plum Brook Station Sandusky, Ohio (50 miles west of Cleveland)



RATF in the Space Power Facility



RATF is the most Powerful Large Reverberant Acoustic Chamber in the World!

(Active) Reverberant Acoustic Test Facility	Location	Volume (ft^3)	Max. OASPL (dB) Empty Chamber	Year Commissioned
Lockheed Martin Missiles and Space, bldg.156, cell no.1, LVATF	Sunnyvale, CA	189,200	156.5	1973
NASA Plum Brook Station	**Sandusky, OH**	**101,200**	**163.0**	**2011**
Lockheed Martin Space Systems	Denver, CO	75,900	154.0	1985
Boeing Satellite Development Center (Boeing SDC)	El Segundo, CA	67,800	155.0	2004
Lockheed Martin Missiles and Space (LMMS), bldg.159	Sunnyvale, CA	64,000	157.3	1996
Mitsubishi Electronics	Kamakura, Japan	61,700	152.0	2002
Large European Acoustic Facility (LEAF) at ESTEC	Noordwijk, The Netherlands	59,000	154.5	1990
Northrop Grumman Space Technology (NGST), LATF	Redondo Beach, CA	51,600	154.0	1996

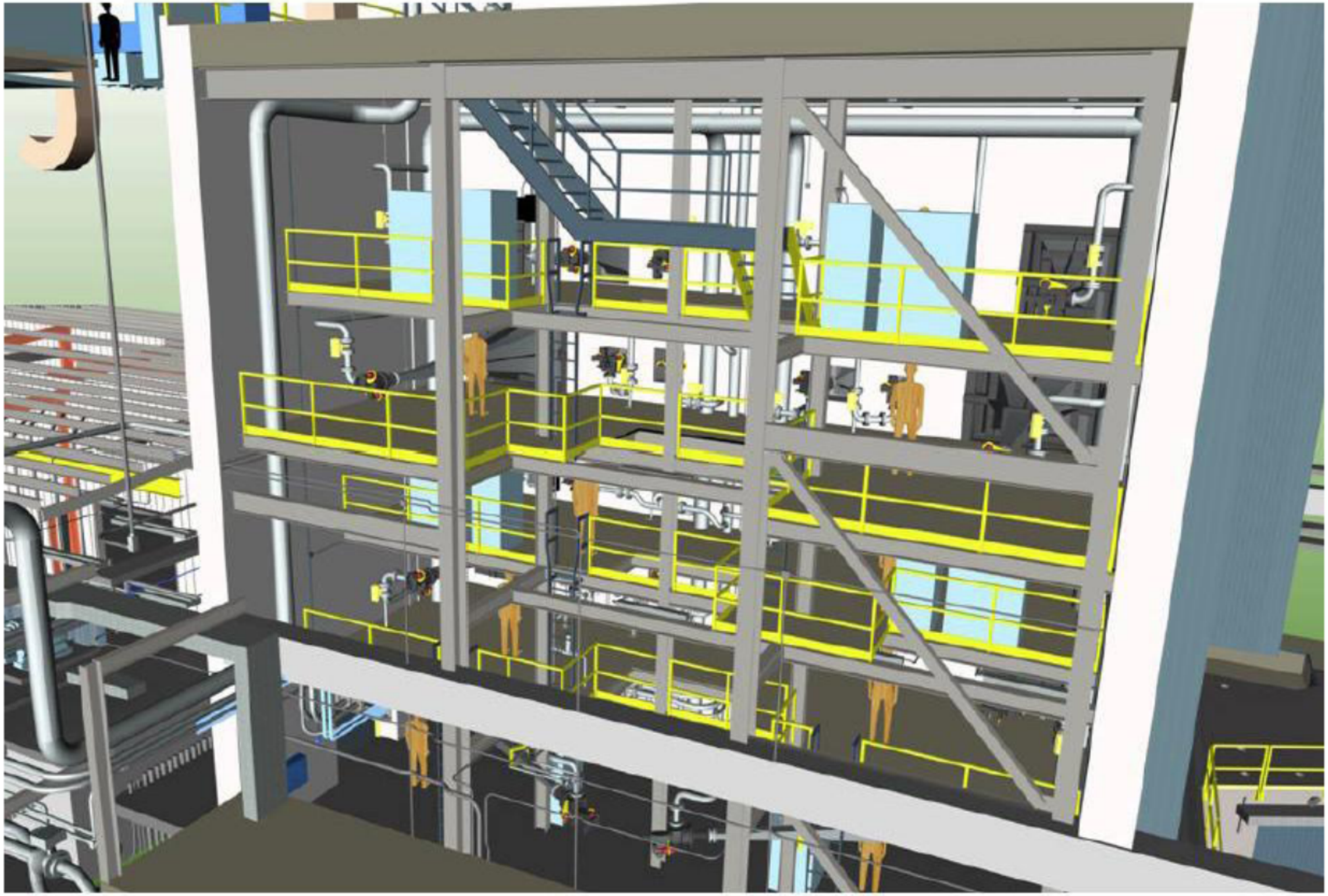
RATF Acoustic Design Features

	Chamber Properties
Chamber Size	47.5 ft L x 37.5 ft W x 57 ft H
Chamber Volume	101,189 ft^3
Acoustic Modulators	23 TEAM Modulators & 13 WAS 5000 Modulators
Horns	36 (grouped at 7 different horn cut-off frequencies)
Maximum GN_2 flow rate	72,000 scfm
Main Door Opening	34.5 ft wide
Number of Main Doors	2
Door Type	Sliding and hinged
OASPL, empty	163 dB OASPL

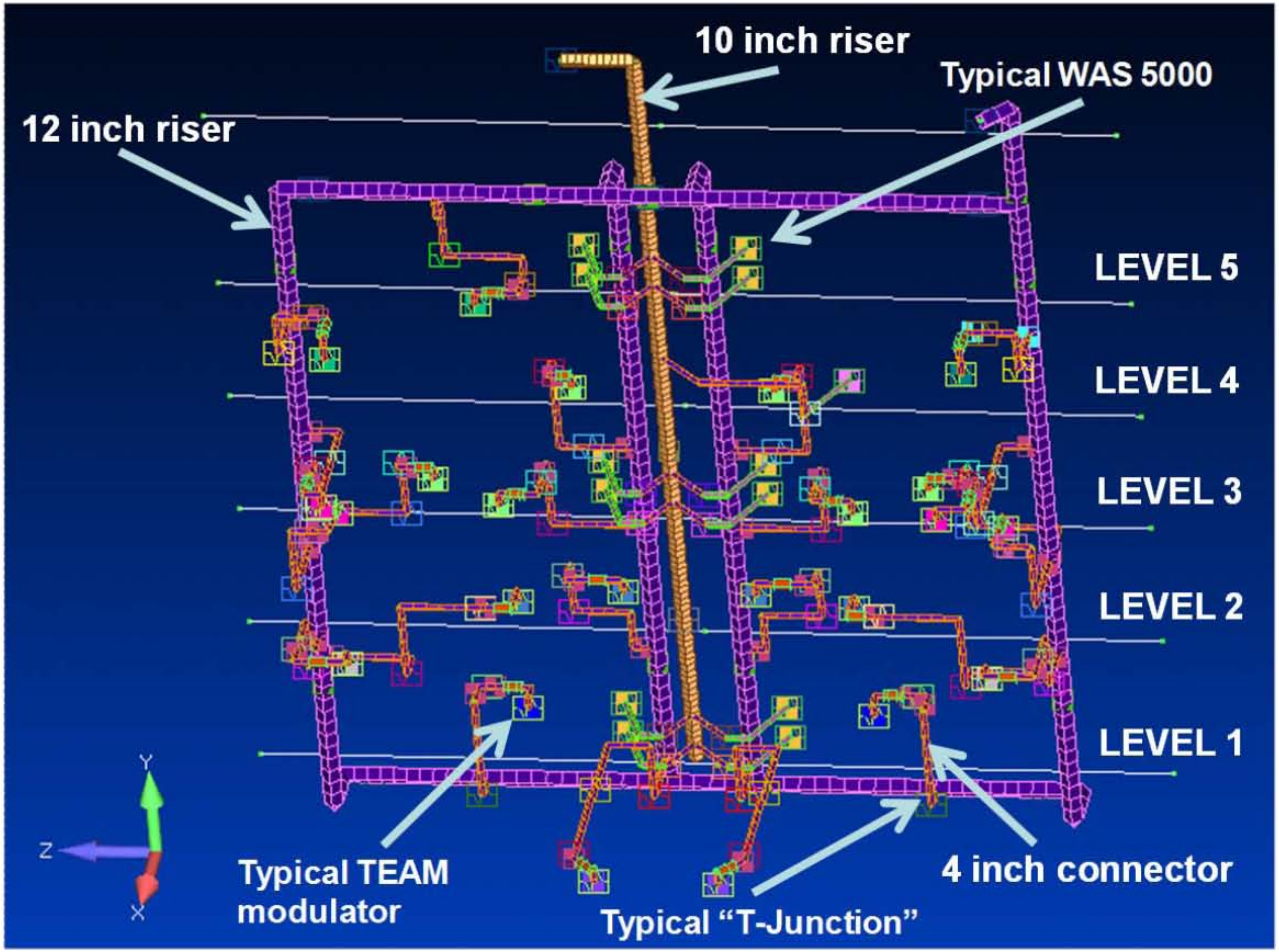
Horn Room Piping Analysis and Repair

RATF Horn Room Illustration

(Cutaway Elevation View of 5 Levels)



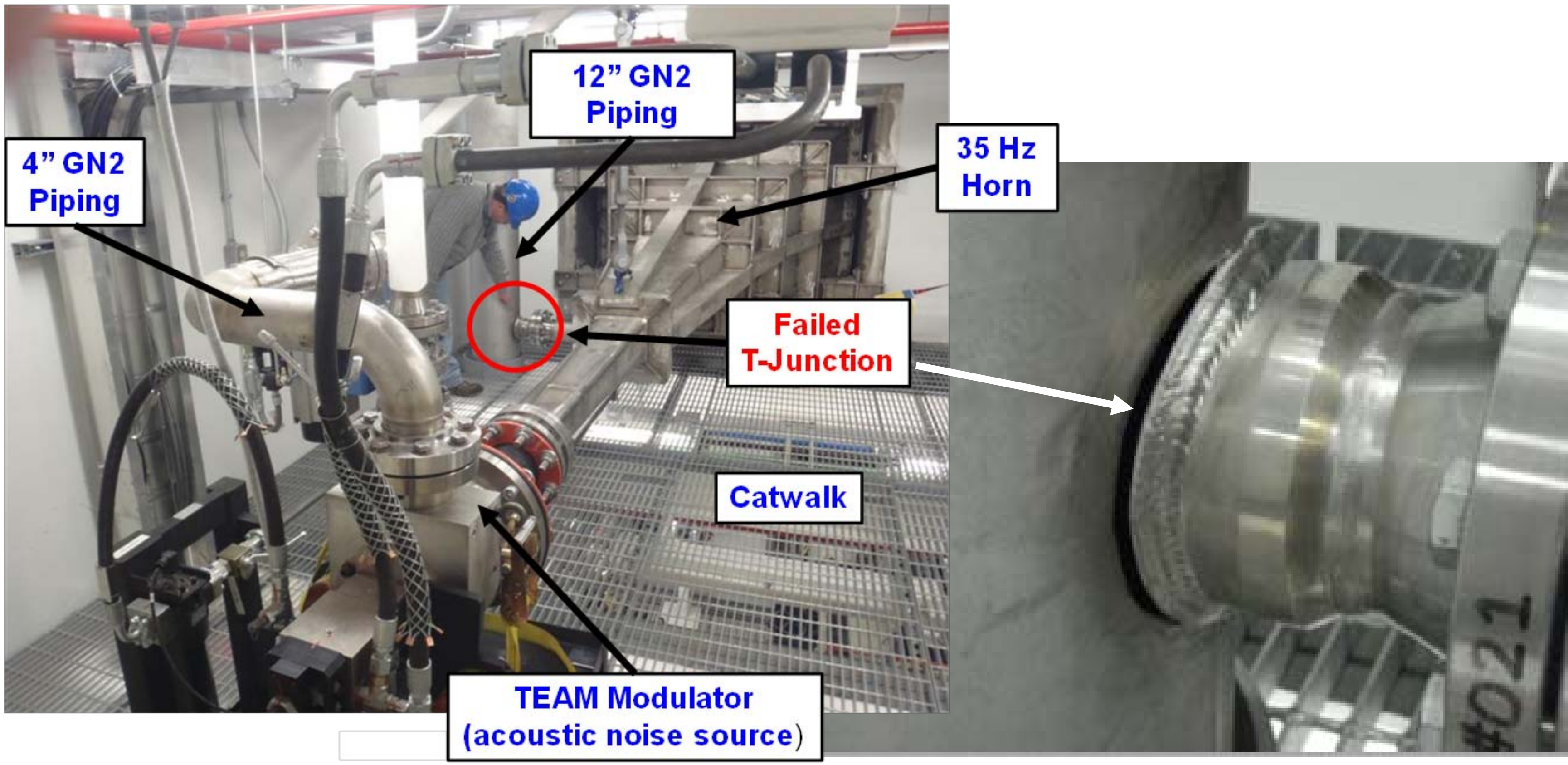
RATF Horn Room Piping System



The 12 inch riser (250 psi pressure) supplies the TEAM modulators.
The 10 inch riser (30 psi pressure) supplies the Wyle WAS 5000 modulators.

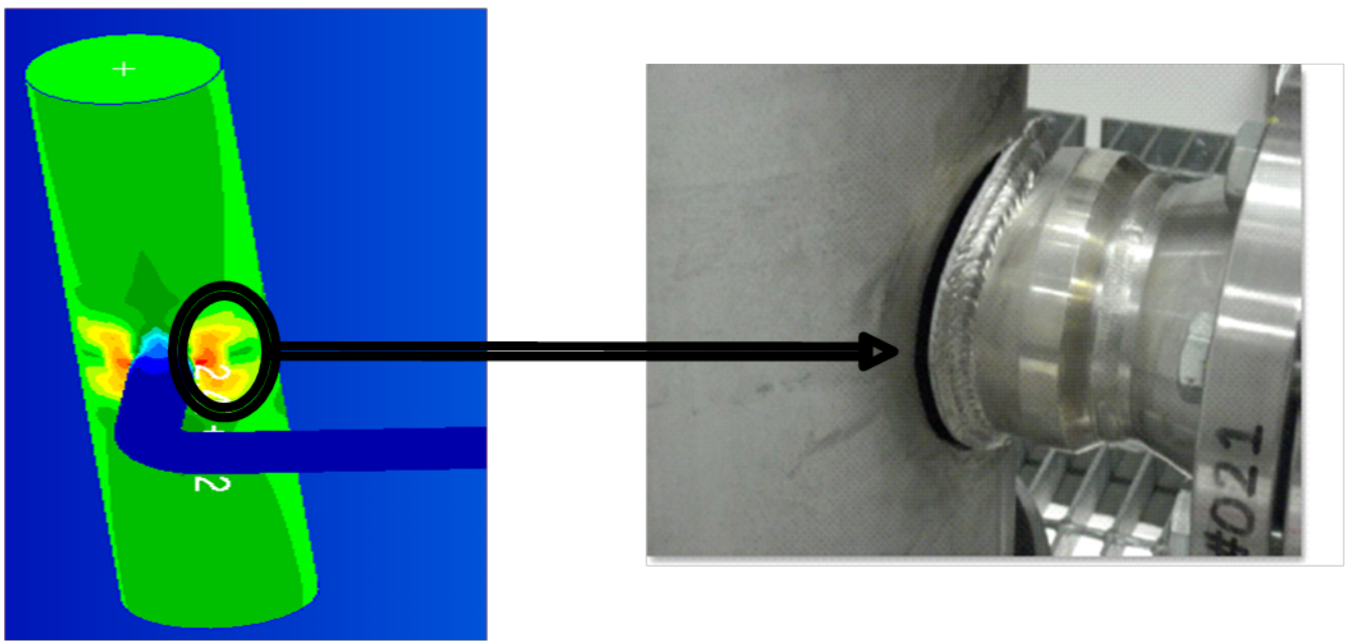
T-Junction Failures

- During initial acoustic checkout testing vibration failures occurred at the T-junction between the 12 inch riser and the 4 inch connector (shown below).
- The piping system was originally constructed of Schedule 10 stainless steel piping.

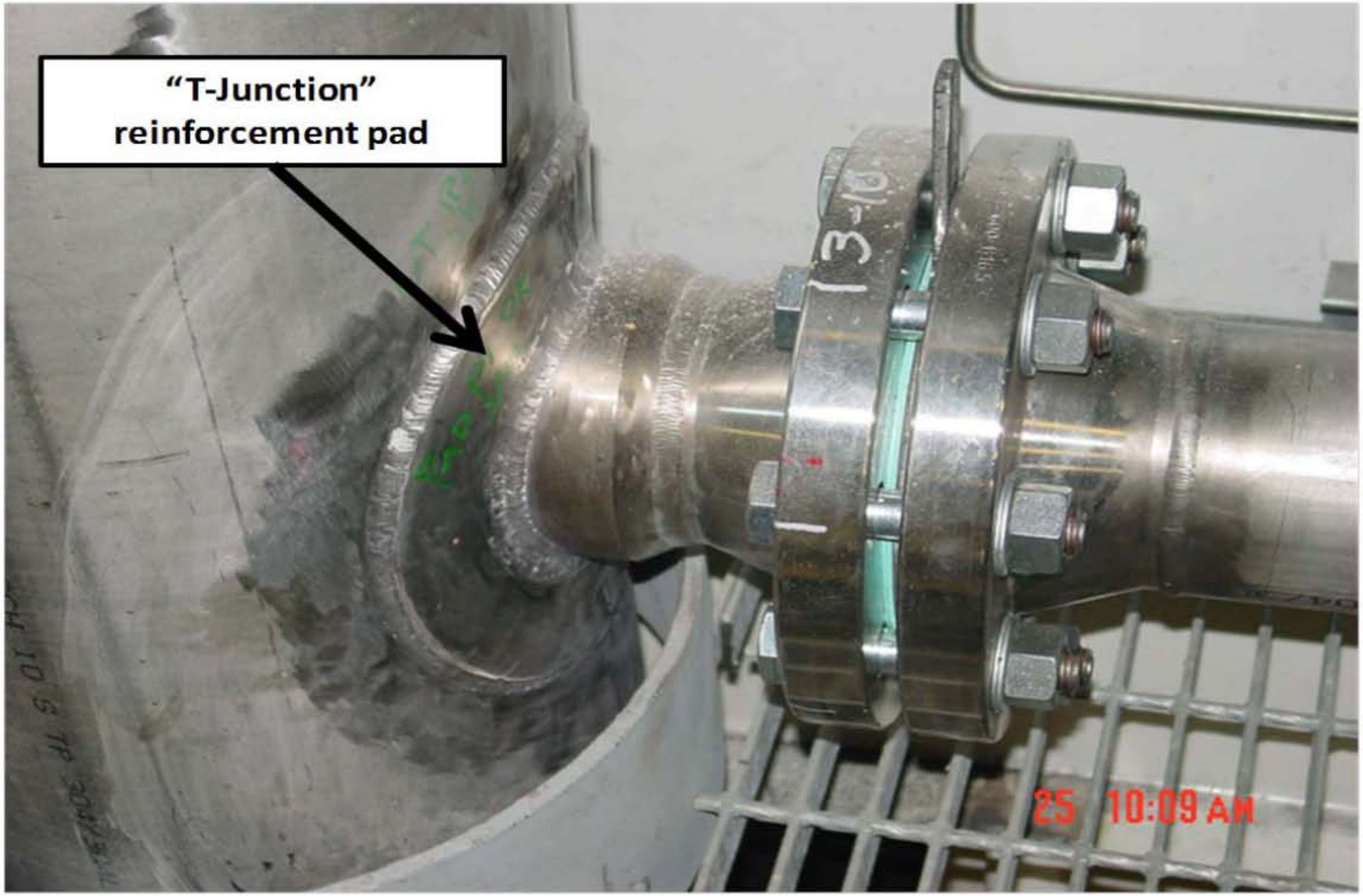


T-Junction Stress Analysis

- A stress analysis of the T-junction indicated **correlation** between the high stress region and the actual failed location.
- For acoustic verification testing, strain gages were installed in the piping system near the T-junctions to monitor stresses. The results of the T-junction stress model was used to select the location of the strain gages.



T-Junction Reinforcement Pad Repair



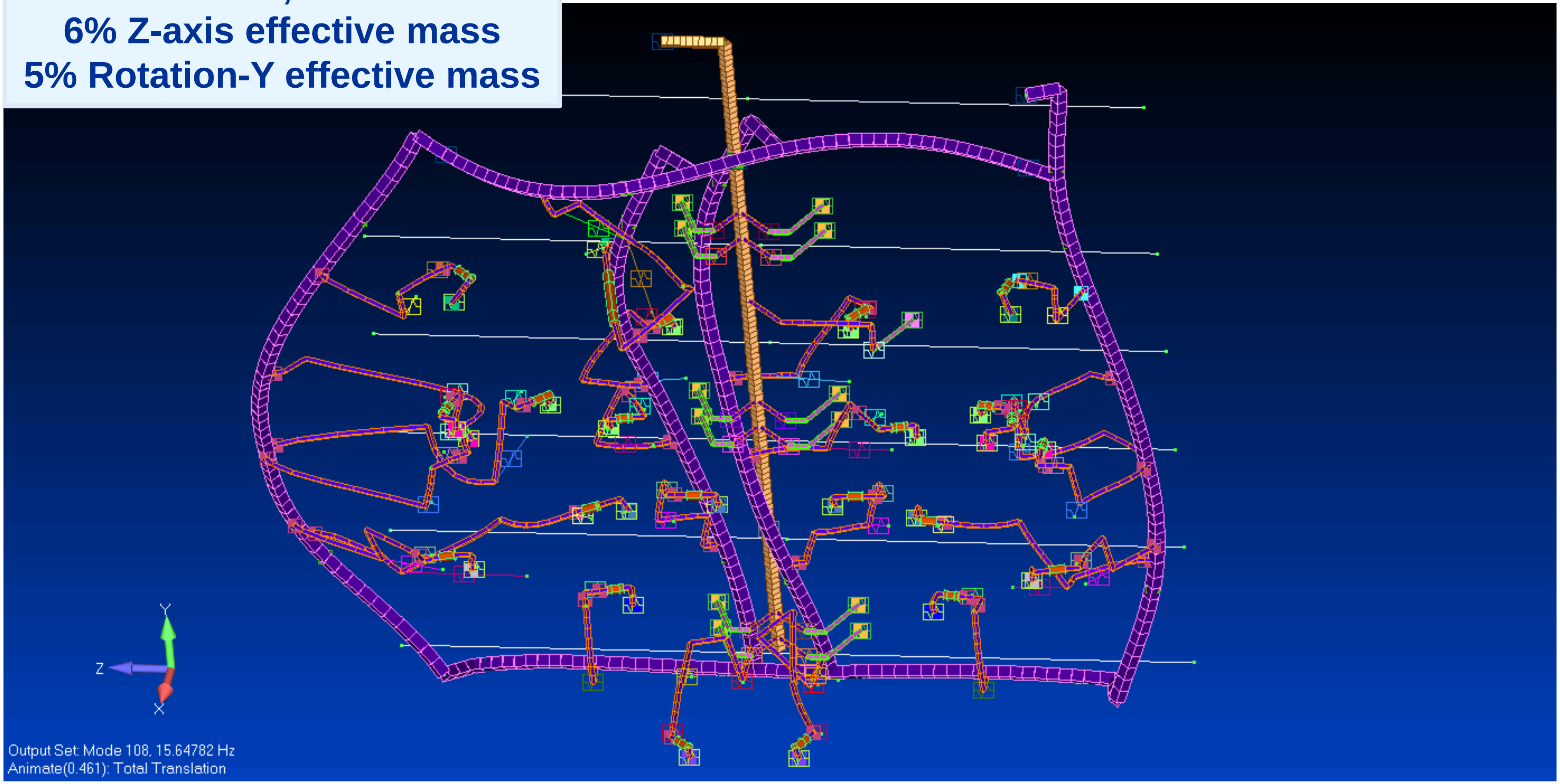
Piping System Dynamic Analysis

- NASA GRC conducted a structural dynamic analysis, after the discovery of the T-Junction failures, to provide additional design recommendations to analyze the piping system modes and decouple, if necessary, from the RATF building (<20 Hz) and catwalk (<17 Hz) structure modes.

- Ten design configuration options were ultimately analyzed to determine the best piping repair solution.

NASTRAN Dynamic Model

Mode 108, 15.65 Hz
6% Z-axis effective mass
5% Rotation-Y effective mass



Original piping design: The 15.65 Hz piping mode is close in frequency to the building and catwalk structural modes.

Configurations Analyzed Summary of Results

LEGEND:
□ = High effective mass piping modes

Configuration Analyzed	Piping System High Effective Mass Modes
1. Baseline Configuration	**10.66 Hz, 15.72 Hz**
2. Adding lateral constraints to TEAM modulators	**10.44 Hz, 15.75 Hz**
3. Removing all constraints from the TEAM modulators	**10.67 Hz, 15.72 Hz**
4. Add 500lb mass to the base of the TEAM modulators	**10.63 Hz, 15.70 Hz**
5. Isolate the TEAM Modulators – **Gamma flex hose**	**10.17 Hz, 15.40 Hz**
6. Isolate the TEAM modulators – **Mason braided flex hose reoriented 90°**	**10.66 Hz, 15.69 Hz**
7. Add new SAIC-Benham recommended pipe supports	**91.22 Hz, 94.19 Hz**
8. Add new SAIC-Benham and NASA recommended pipe supports	**91.32 Hz**
9. **Combine #6 and #8**: New SAIC-Benham and NASA recommended pipe supports **Mason braided flex hose reoriented 90°**	**91.31 Hz**
10. **Combine #5 and #8**: New SAIC-Benham and NASA recommended pipe supports with soft connection to TEAM modulators using **Gamma flex hose**	**90.43 Hz**

Adding piping supports increases piping modes frequency > 90 Hz, decoupling the piping system response from the RATF building and catwalk modes. Configuration #8 was chosen for the piping repair.

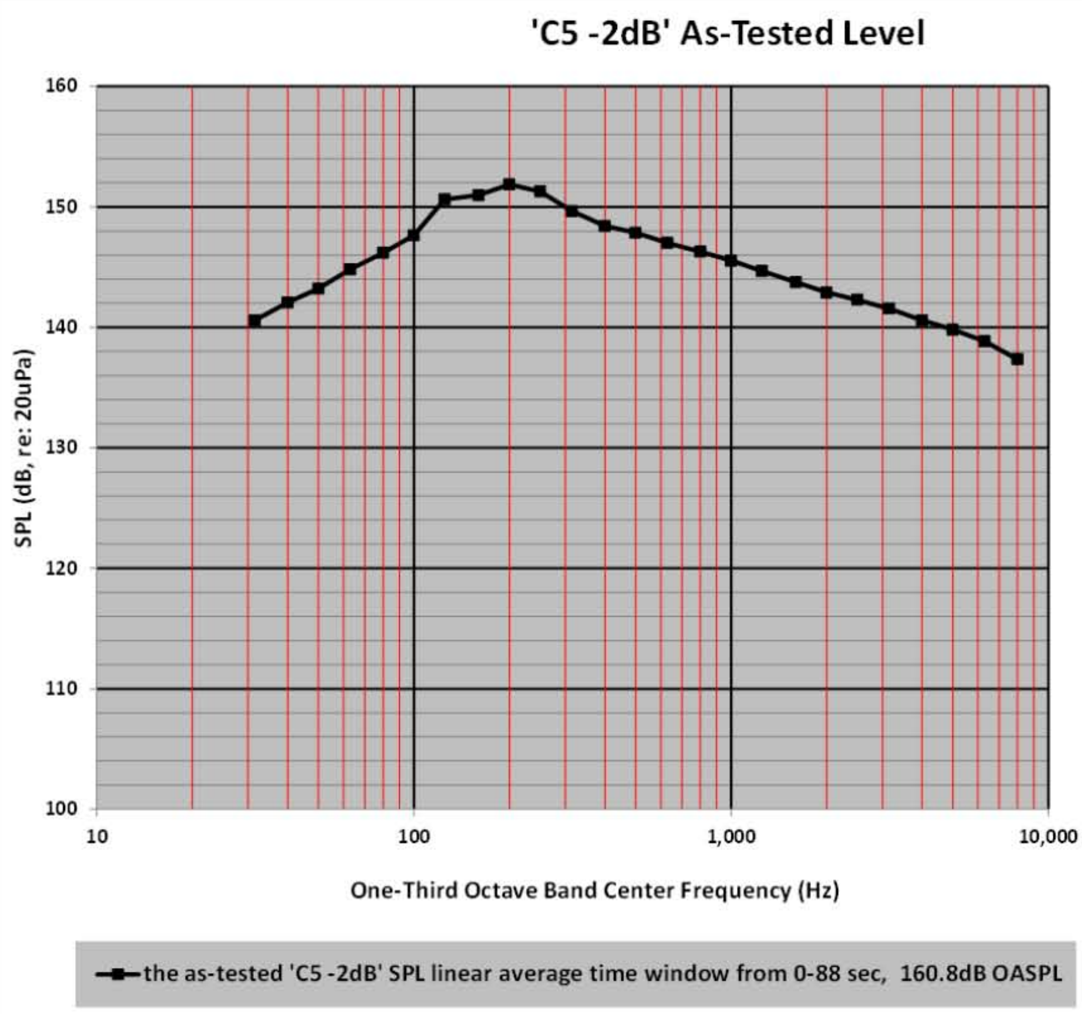
Horn Room Piping Repairs

SAIC-Benham’s repair of the piping system (Configuration #8) included:

1. “T-junction” reinforced pad repair at all locations
2. SAIC-Benham recommended 24 additional pipe supports on the 12 inch risers
3. NASA recommended 4 additional pipe supports on the 12 inch risers
4. Additional 4 inch branch pipe supports near elbows or long unsupported runs
5. Schedule 40 piping was added at the highly stressed elbows of the 4 inch branch

Acoustic Verification Testing

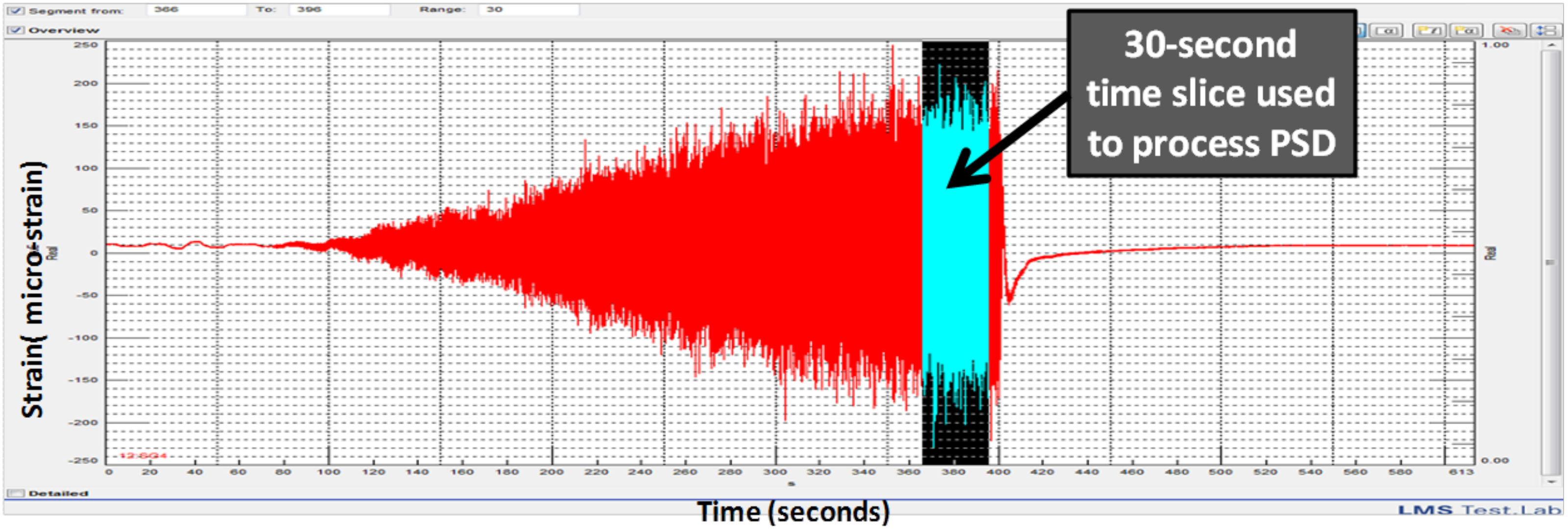
RATF Acoustic Verification Testing

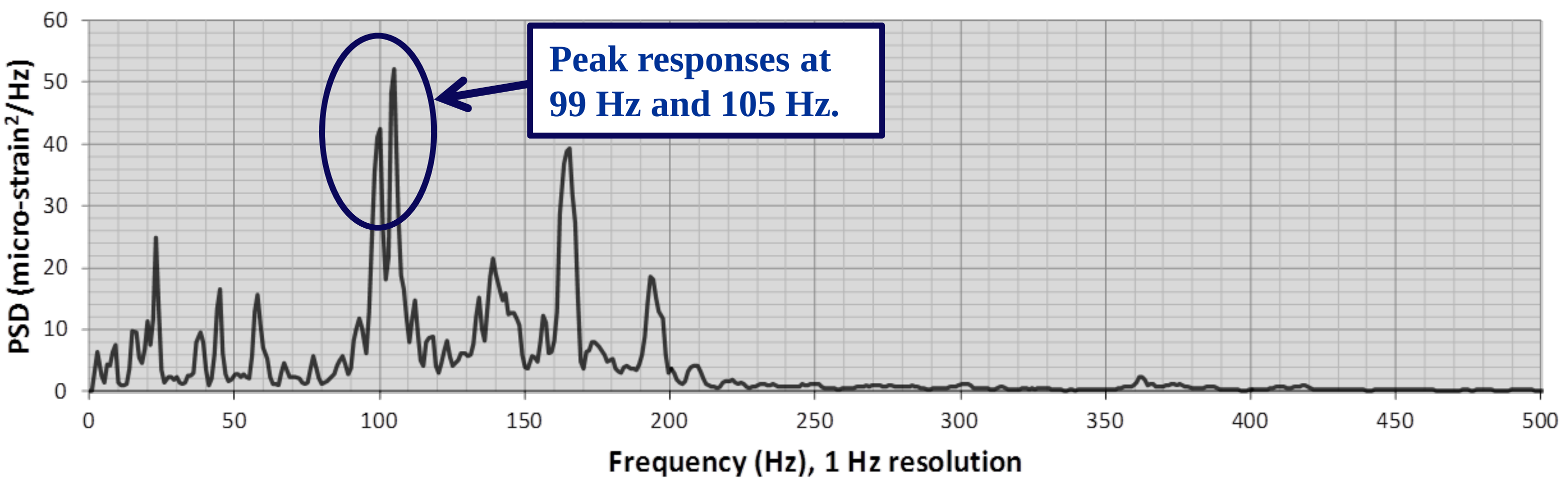


One-Third Octave Band Center Frequency (Hz)	the as-tested 'C5 -2dB' SPL linear average time window from 0-88 sec, 160.8dB OASPL
31.5	140.6
40	142.1
50	143.2
63	144.8
80	146.2
100	147.6
125	150.6
160	151.0
200	151.9
250	151.3
315	149.7
400	148.4
500	147.9
630	147.0
800	146.3
1,000	145.5
1,250	144.7
1,600	143.8
2,000	142.9
2,500	142.3
3,150	141.6
4,000	140.6
5,000	139.8
6,300	138.8
8,000	137.3
OASPL	160.8

RATF acoustic verification testing achieved 160.8 dB OASPL.

RATF Acoustic Verification Testing





T-Junction strain measurements indicate resonant modes at 99 Hz and 105 Hz, validating the finite element model and redesign goal of moving the major piping system modes to greater than 90 Hz.

Summary

- The dynamic coupling between the piping system's original high effective mass modes (10 and 15 Hz) and RATF building (< 20 Hz) and catwalk (< 17 Hz) structure modes contributed to the failure of the piping system.
- The piping system's T-Junction repairs and additional piping supports were implemented based on extensive dynamic analysis.
- Subsequent test measurements verified that the piping system's modes and RATF building modes have been successfully decoupled. The facility was commissioned September 2011.

Reference:

"**Structural Dynamic Assessment of the GN2 Piping System for NASA's New and Powerful Reverberant Acoustic Test Facility,"** by Mark E. McNelis, Lucas D. Staab, Dr. James C. Akers, William O. Hughes, Li C. Chang, Aron D. Hozman, and Michael W. Henry, NASA Glenn Research Center, Cleveland, Ohio, NASA Technical Memorandum 2012-217610, June 2012.

"**The Development of the Acoustic Design of NASA Glenn Research Center's New Reverberant Acoustic Test Facility**," by William O. Hughes, Mark E. McNelis, Aron D. Hozman, and Anne M. McNelis, NASA Glenn Research Center, Cleveland, Ohio, NASA Technical Memorandum 2011-217000, July 2011.

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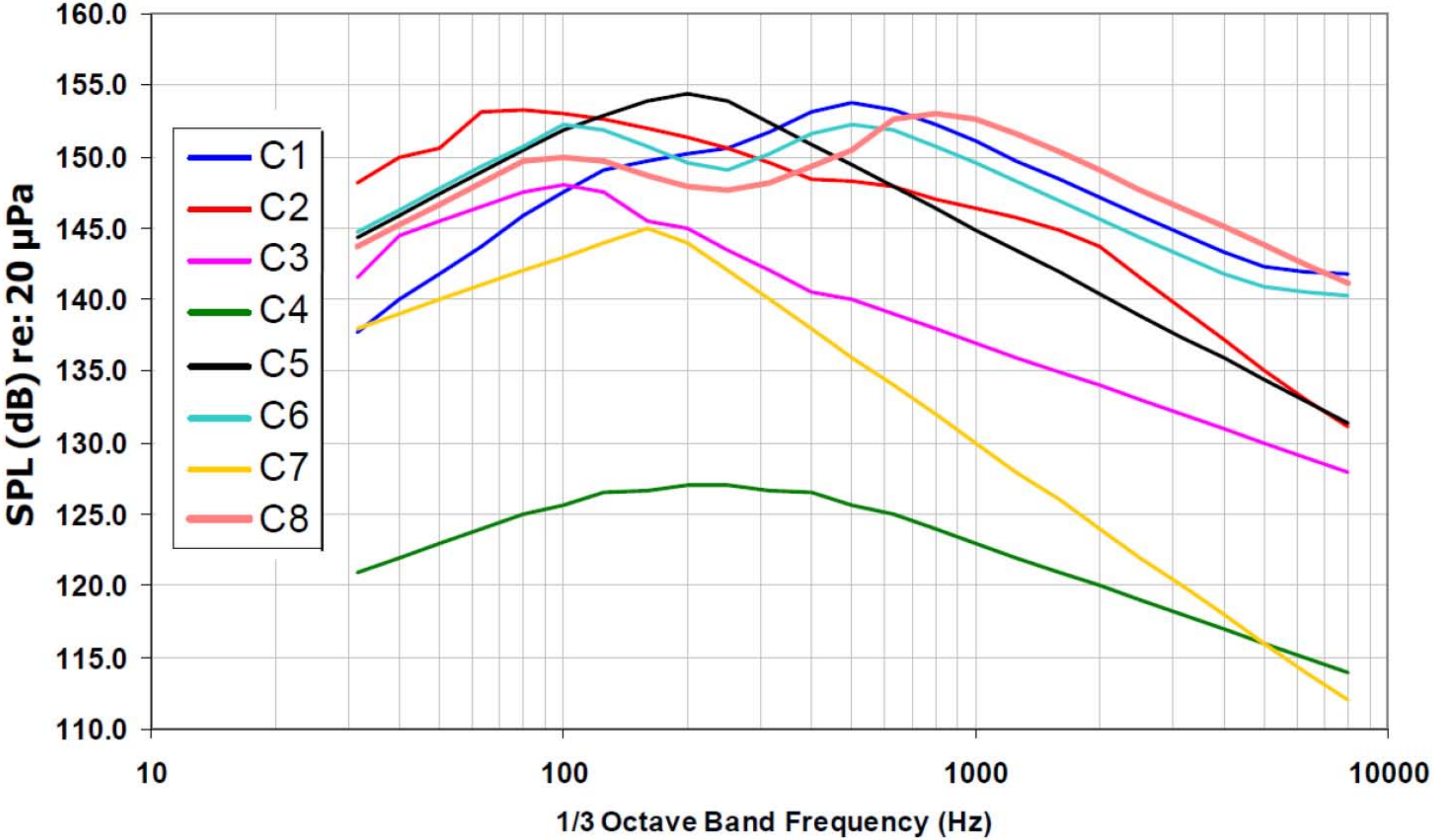
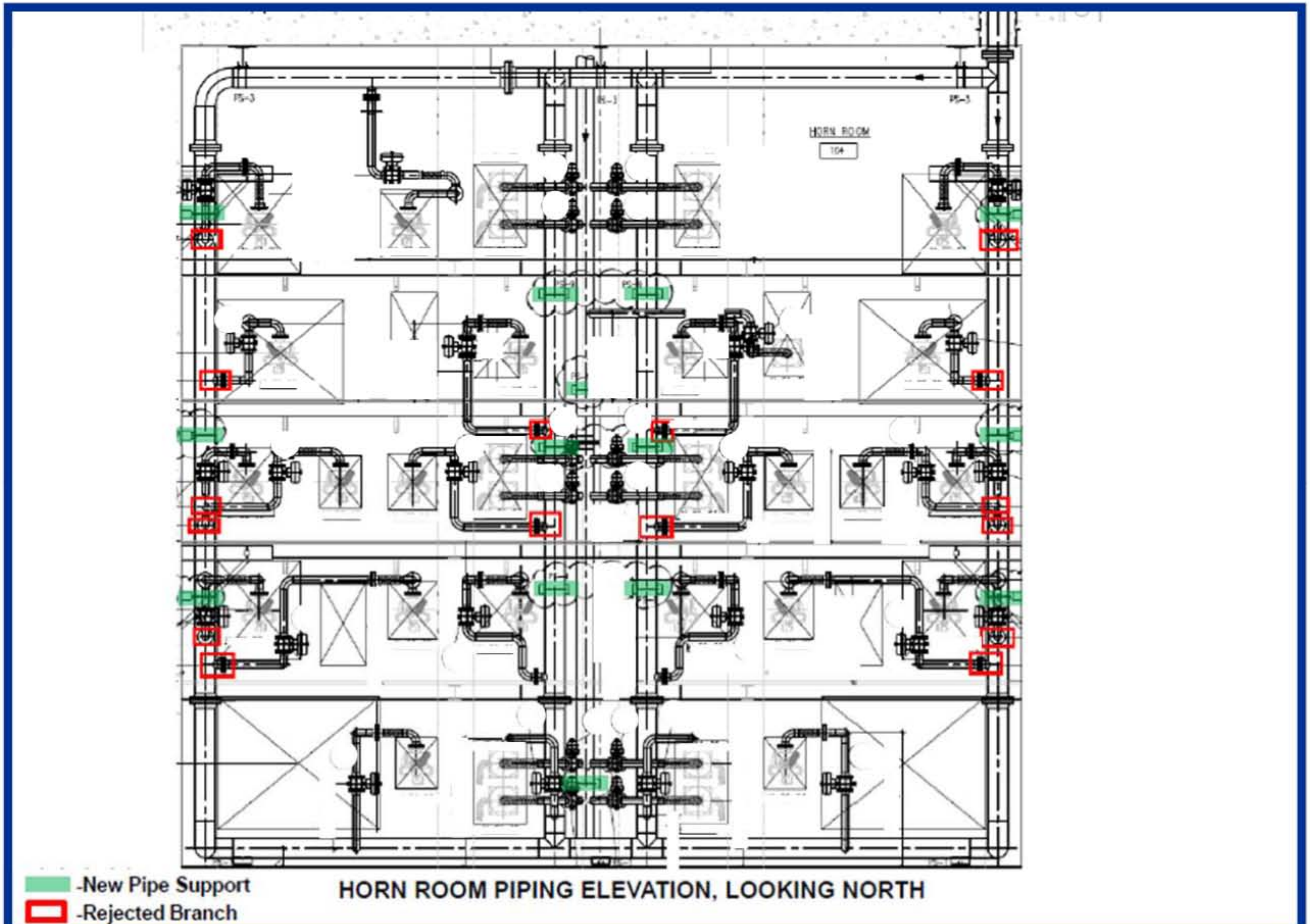
Back Up Slides

RATF Acoustic
"C" Spectra Design Requirements



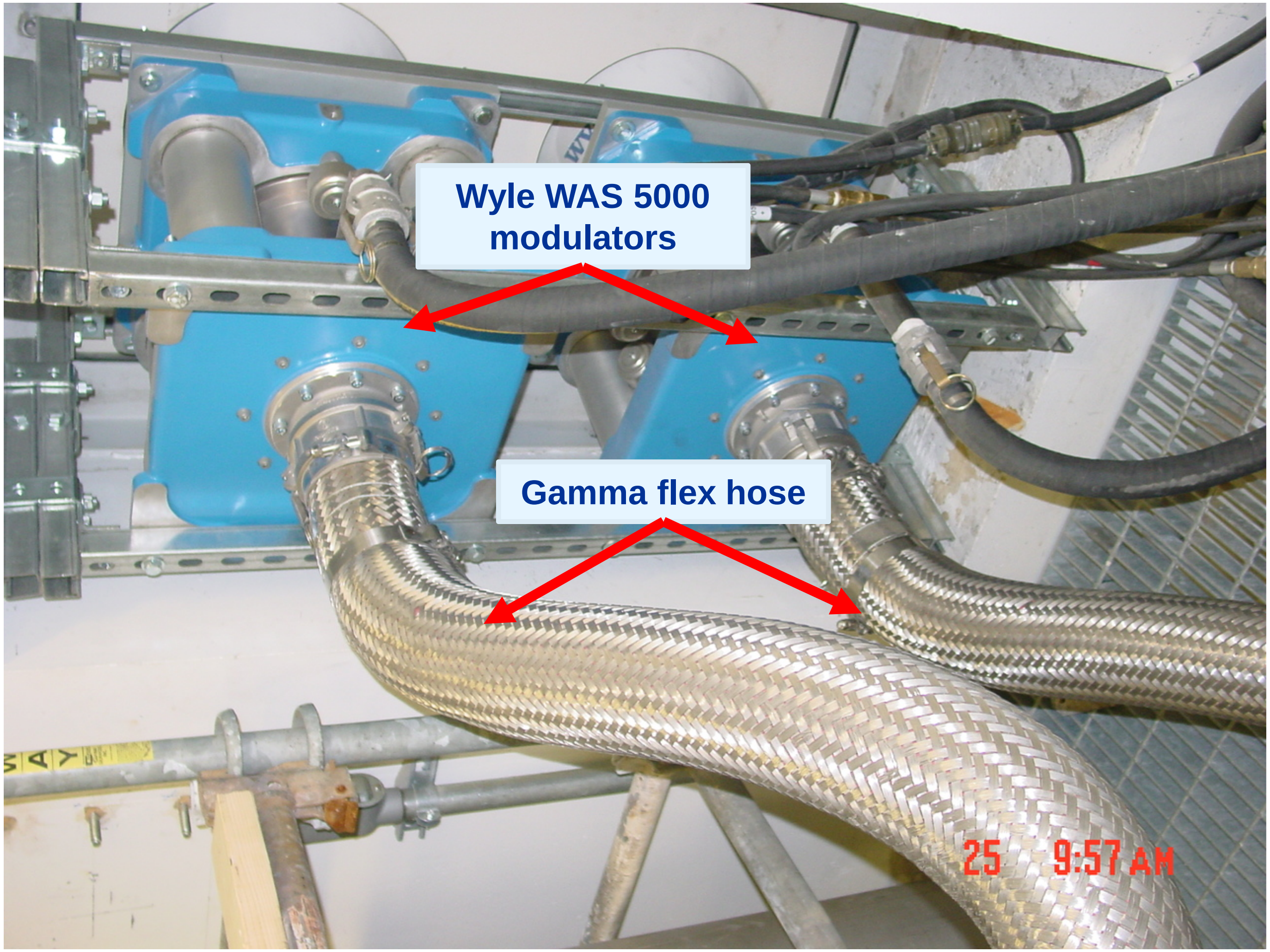
The C1-C8 test spectra provide a wide range of test curves, each providing a unique spectral control challenge. C2 has the highest low frequency SPL value.

T-Junction Failures (in red) from initial Acoustic Checkout Testing



Gamma Flex Hose

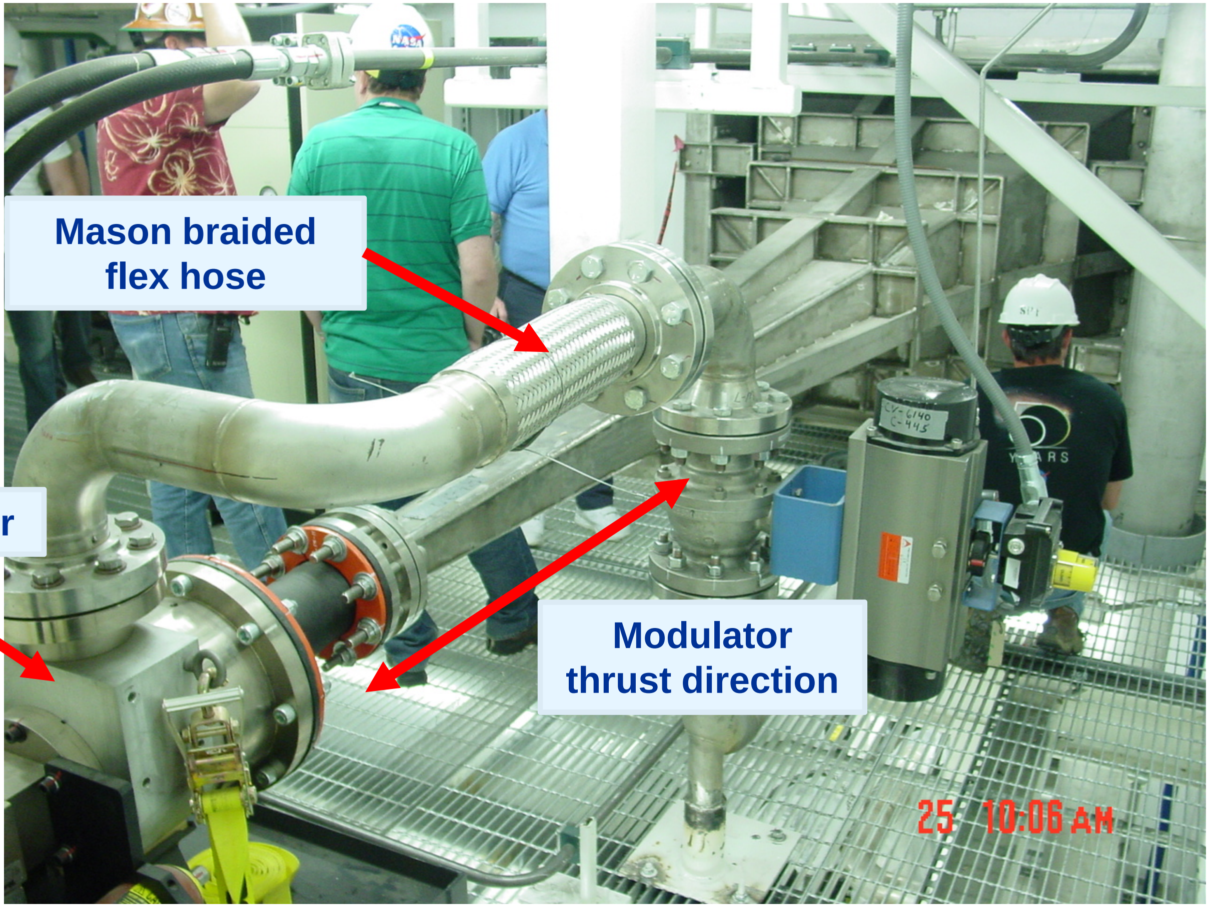
Configuration #5. Isolate the TEAM modulators



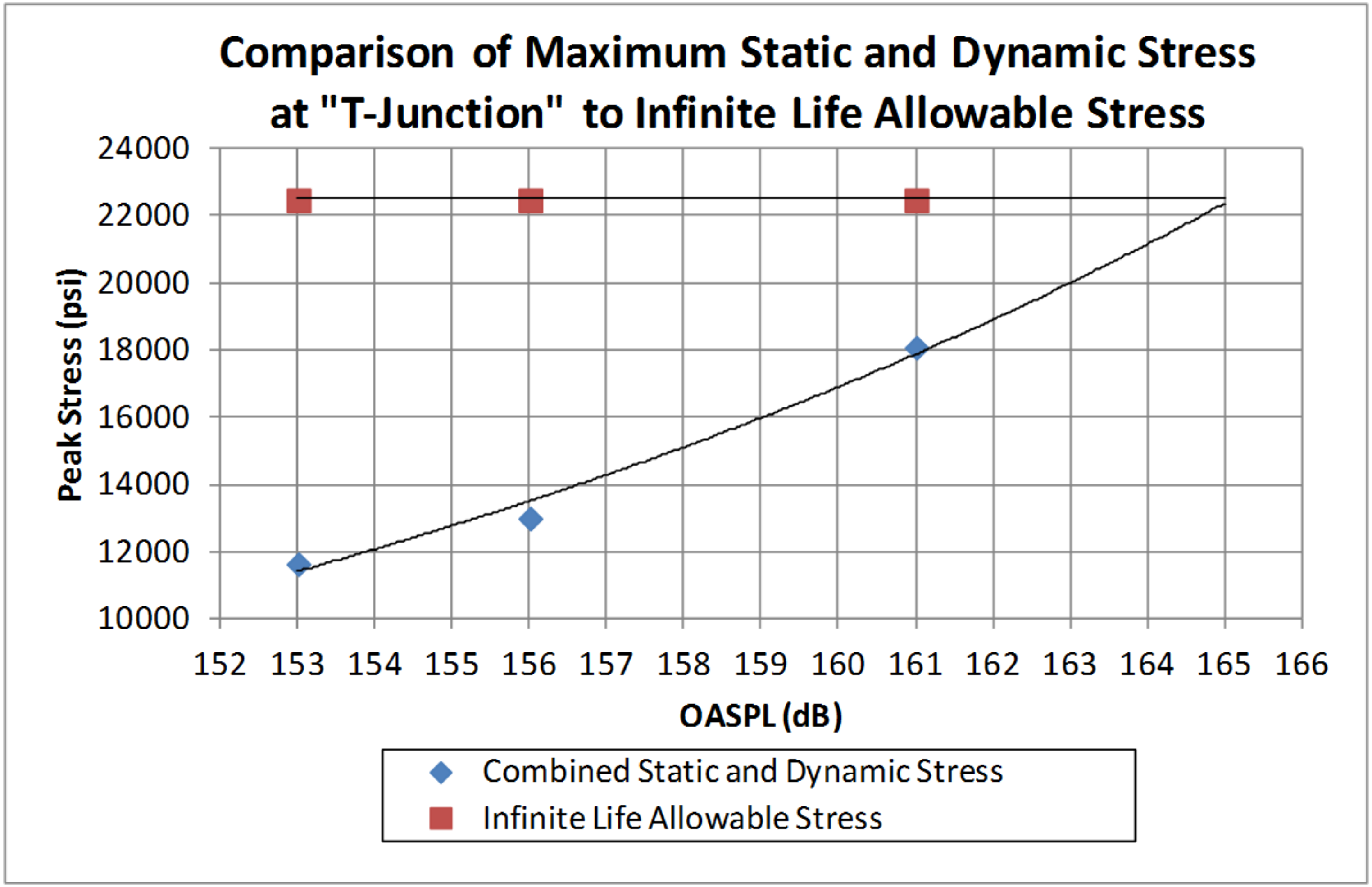
The Gamma flex hose provides a soft, flexible connection (4” bend radius) to the Wyle WAS 5000 modulators.

Mason Braided Flex Hose

Configuration #6. Isolate the TEAM modulators



Recommended reorienting the flex hose to be perpendicular to the modulator thrust direction to limit piping vibration fatigue.



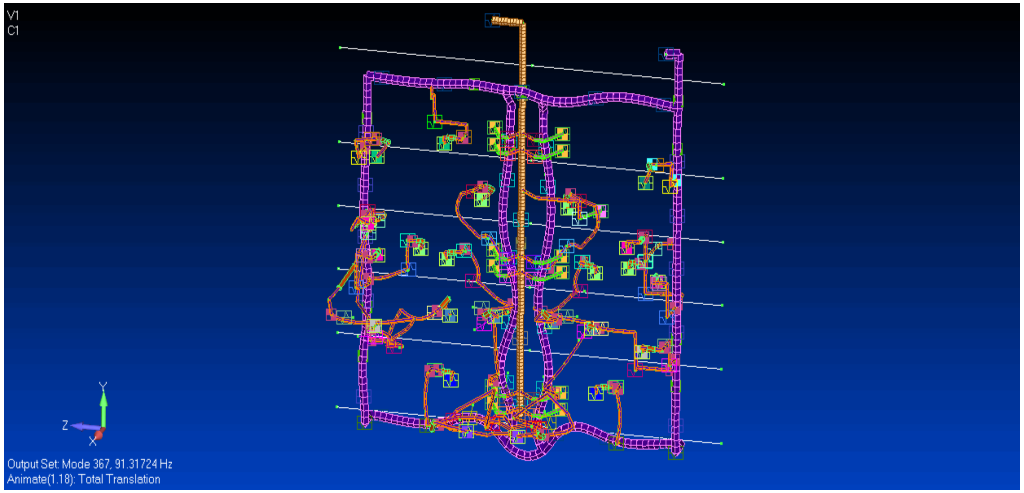
- **T-junction strain measurements indicate the piping system can withstand up to 165 dB OASPL for infinite fatigue life (10^7 alternating stress cycles).**
- **Results are dependent on the shape of the acoustic test spectrum (C7 and C5 tested); test spectra with larger low frequency acoustic levels could alter this conclusion.**

Configuration Analyzed

8. Add new Benham and NASA recommended pipe supports

- Modal effective mass summary: 393 modes, 0-100 Hz, 75% X, 25%Y, 73% Z

Description	Frequency (Hz)
TEAM Modulator Piping Modes	3.05-100.19 Hz
WAS 5000 Modulator Piping Modes	3.91-100.21 Hz
Piping System High Effective Mass Modes	30.96 Hz, 31.11 Hz, **91.32 Hz**



Mode 367, 91.32 Hz
8% Y-axis effective mass
7% Rotation-X effective mass
8% Rotation-Z effective mass

High effective mass piping modes are increased to 90 Hz or greater, decoupling from the RATF building and catwalk modes.